

# Measurement of $\epsilon'/\epsilon$ by the KTeV Experiment

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B Physics and CP Violation

KTeV Collaboration:  
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UCSD, Virginia, Wisconsin

## TWO KINDS OF CP VIOLATION

- **MIXING**  $|\mathcal{K}_L\rangle \sim |\mathcal{K}_2\rangle + \epsilon |\mathcal{K}_1\rangle$   
 $\rightarrow \pi\pi$

Interference Between  $\mathcal{K}^0 \rightarrow \pi\pi$   
 $\mathcal{K}^0 \rightarrow \bar{\mathcal{K}}^0 \rightarrow \pi\pi$

- **DIRECT**  $|\mathcal{K}_L\rangle \sim |\mathcal{K}_2\rangle + \epsilon |\mathcal{K}_1\rangle$   
 $\rightarrow \pi\pi$

Interference Between  $\mathcal{K}^0 \xrightarrow{I=0} \pi\pi$   
 $\mathcal{K}^0 \xrightarrow{I=2} \pi\pi$

$$\epsilon' \sim \text{Arg } (\mathcal{K}^0 \xrightarrow{I=0} \pi\pi) - \text{Arg } (\mathcal{K}^0 \xrightarrow{I=2} \pi\pi)$$

$$\eta_{00} = \frac{\langle \pi^0 \pi^0 | T | \mathcal{K}_L \rangle}{\langle \pi^0 \pi^0 | T | \mathcal{K}_S \rangle} = \epsilon - 2\epsilon'$$

$$\eta_{+-} = \frac{\langle \pi^+ \pi^- | T | \mathcal{K}_L \rangle}{\langle \pi^+ \pi^- | T | \mathcal{K}_S \rangle} = \epsilon + \epsilon'$$

$$\Re(\epsilon'/\epsilon) = \frac{1}{6} \left\{ 1 - \frac{\Gamma(\mathcal{K}_L \rightarrow \pi^0 \pi^0) / \Gamma(\mathcal{K}_S \rightarrow \pi^0 \pi^0)}{\Gamma(\mathcal{K}_L \rightarrow \pi^+ \pi^-) / \Gamma(\mathcal{K}_S \rightarrow \pi^+ \pi^-)} \right\}$$

## KTeV Experimental Method

Exploit the double ratio

$$\frac{K_L \rightarrow \pi^0 \pi^0 / K_S \rightarrow \pi^0 \pi^0}{K_L \rightarrow \pi^+ \pi^- / K_S \rightarrow \pi^+ \pi^-}$$

- Double Beam Technique  
Simultaneous  $K_L$  and  $K_S$  Beams

Alternating Beams

Detector Drifts, Inefficiencies, and Asymmetries  
(almost) Cancel

- Simultaneous Charged and Neutral

Beam Intensity and  $K_S$  Production Cancel

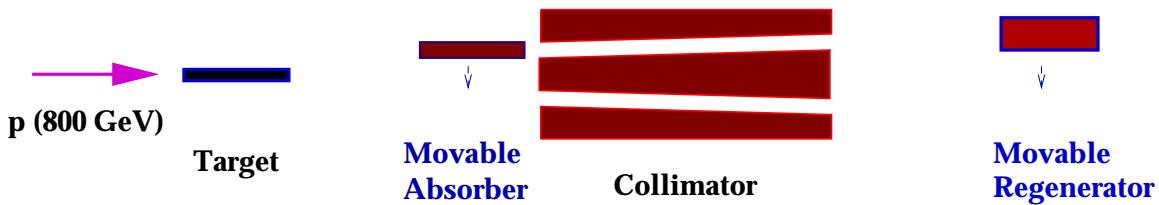
- Acceptance Corrections

Correct for Difference in  $K_L$  vs.  $K_S$  Decay  
Distribution using Simulation; understand  
Simulation using  $K_L \rightarrow \pi^0 \pi^0 \pi^0$ ,  $K_L \rightarrow \pi^\pm e^\mp \nu$  decays

- $K_L$  vs.  $K_S$  Identification

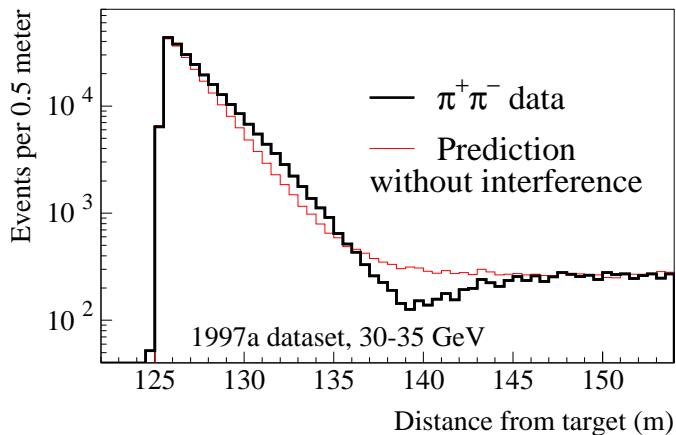
Two neutral beams separated by 15 cm  
Background from Incoherent Regeneration

## KTeV Beam



$K_S$  produced by Regeneration  $K_L + \rho K_S$   
 regeneration occurs since  $\sigma(K^0 C^{12}) \neq \sigma(\bar{K}^0 C^{12})$

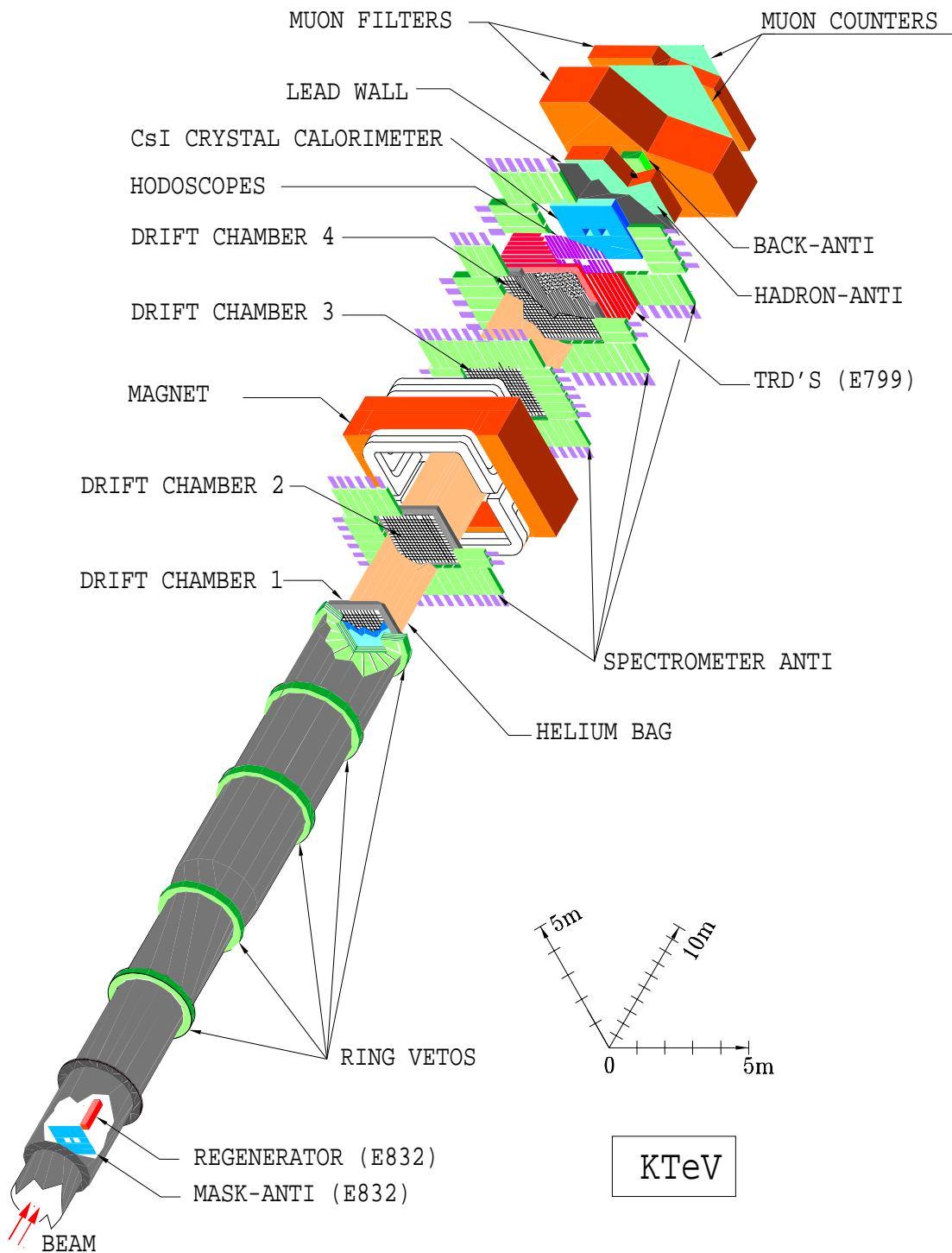
$$|\rho| \sim 1.3 \left\{ \frac{E(\text{GeV})}{70} \right\}^{-0.6} \text{ mb}$$



$$\text{Rate}(\tau) = \Gamma_s \left\{ |\eta|^2 e^{-\Gamma_L \tau} + |\rho|^2 e^{-\Gamma_s \tau} + 2|\rho||\eta| e^{-(\Gamma_s + \Gamma_L)\tau/2} \cos(\Delta m \tau - \phi + \phi_\rho) \right\}$$

- Coherent  $P_\tau^2 = 0$   
 Identical  $K_S$  and  $K_L$  Beam Profiles
- Diffractive  $P_\tau^2 > 0$  and Inelastic  
 Background, especially in  $K \rightarrow \pi^0 \pi^0$

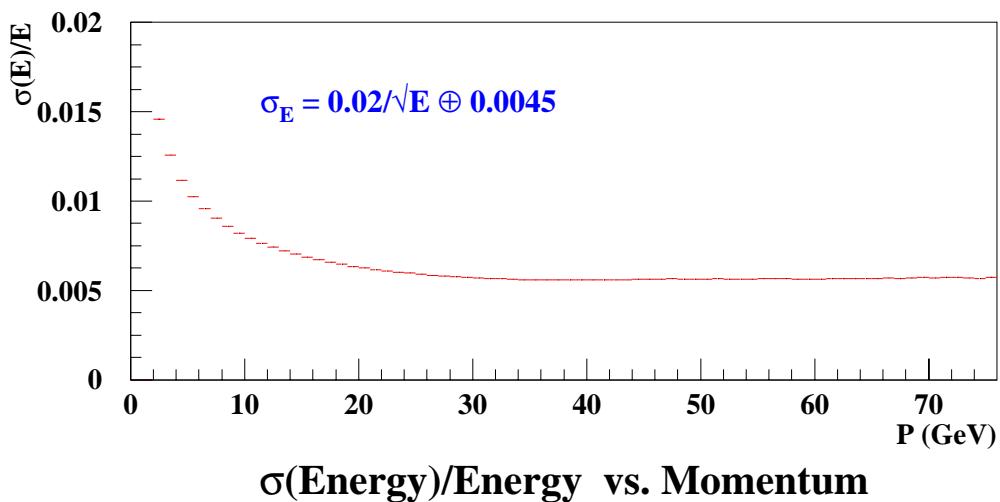
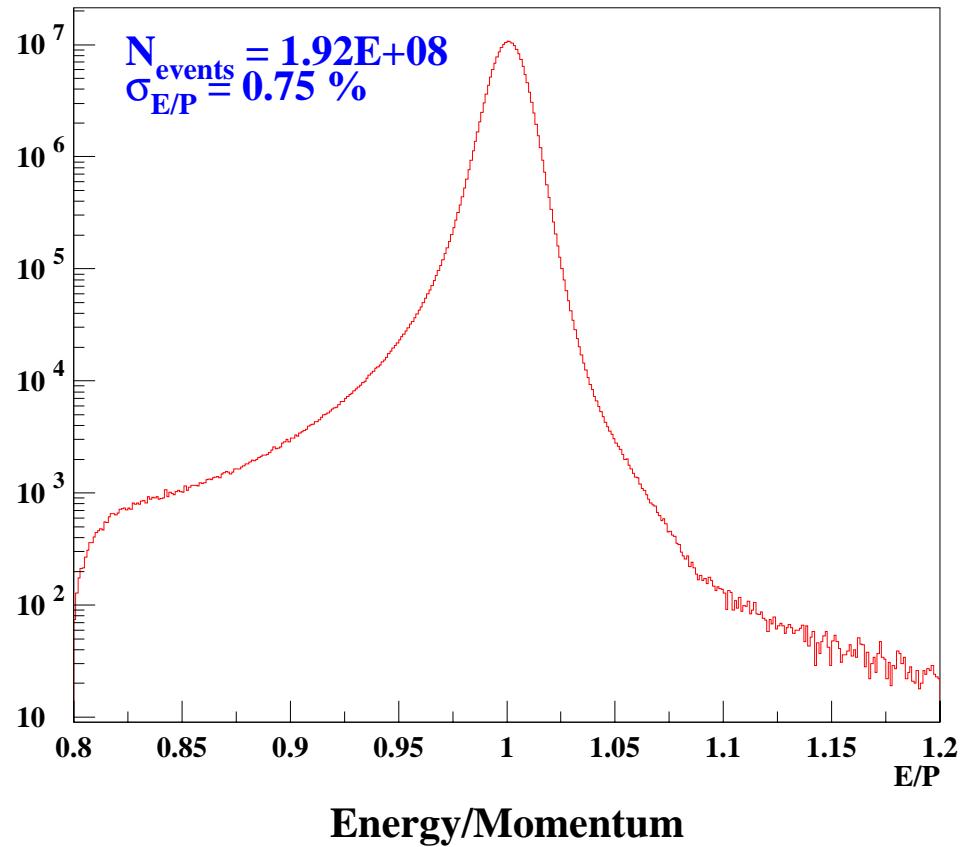
# KTeV Detector



KTeV

## CsI Calorimeter Performance

### Electrons from $K \rightarrow \pi e\nu$



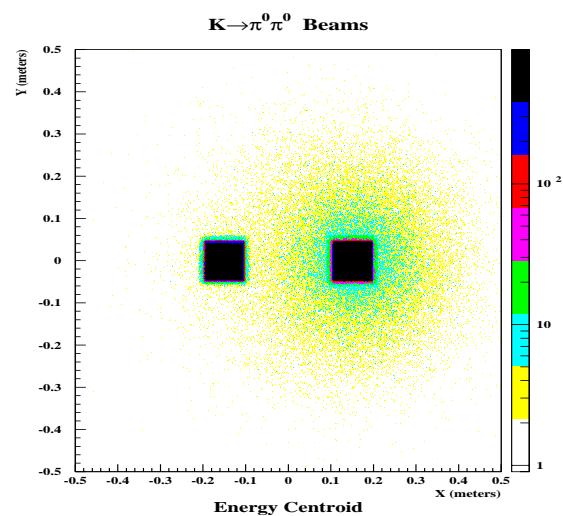
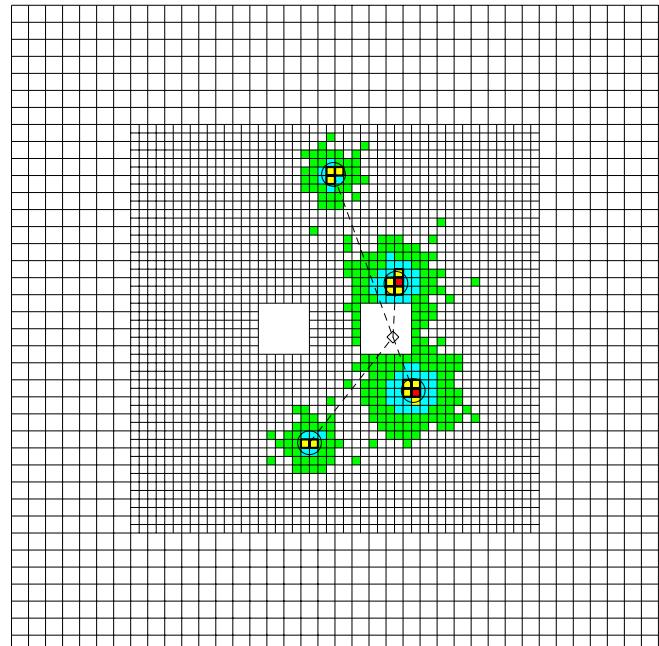
## $K \rightarrow \pi^0\pi^0$ Reconstruction

Use  $\pi^0$  Mass constraint to select best Pairing of 4  $\gamma$  into 2  $\pi^0$

$$Z^2 = \frac{E_1 E_2 (D_{12})^2}{M_{\pi^0}^2}$$

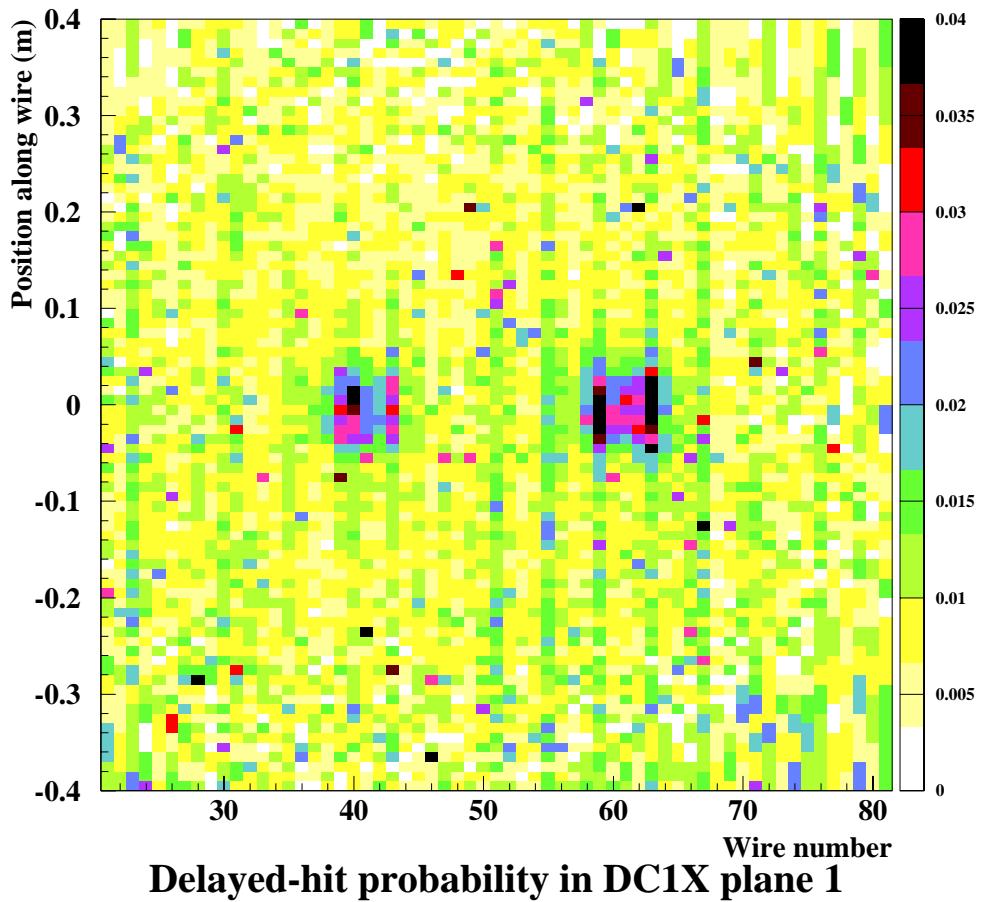
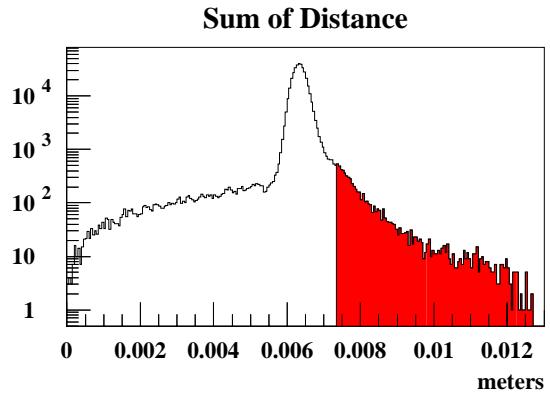
$$\chi^2 = \frac{(Z_a - Z_b)^2}{\sigma_{Z_a}^2 + \sigma_{Z_b}^2}$$

- Measure  $Z_{\pi^0\pi^0}$
- Measure  $M_{\pi^0\pi^0}$
- Measure Energy Centroid  $X_{\pi^0\pi^0}$  and  $Y_{\pi^0\pi^0}$



## Drift Chamber Problems

The Drift Chamber threshold was somewhat greater than one ionization electron, which caused delayed hits.



The Drift Chamber delayed hit probability and hit inefficiencies were mapped using data, and the maps were used in the simulation.

# $K \rightarrow \pi^+\pi^-$ Reconstruction

## KTEV Event Display

/cp/dk2b/data/R06918\_2PI\_100  
k.good

Run Number: 6918  
Spill Number: 1  
Event Number: 36632  
Trigger Mask: 1  
All Slices

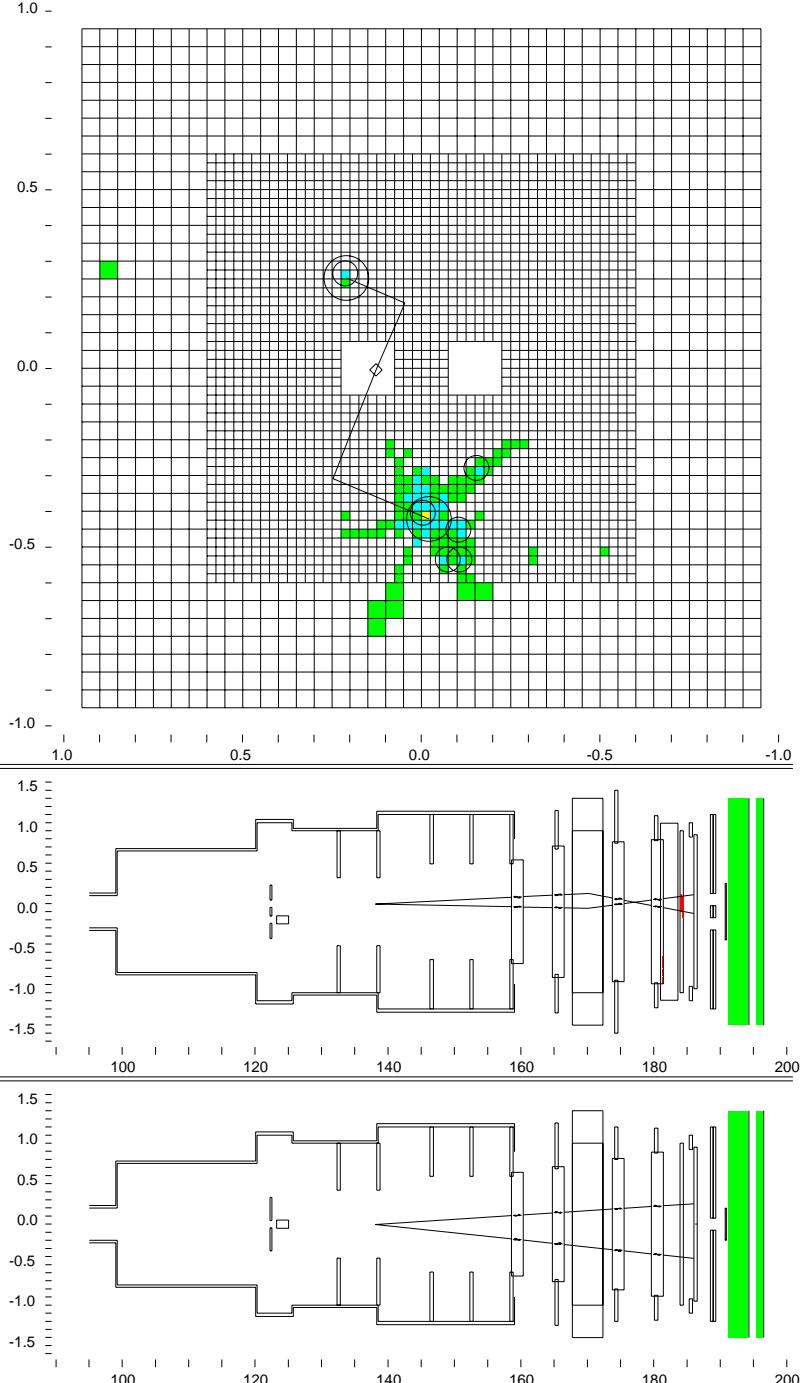
### Track and Cluster Info

HCC cluster count: 0  
ID Xcsi Ycsi P or E  
 T 1: 0.2100 0.2526 -34.05  
 C 1: 0.2129 0.2659 0.45  
 T 2: -0.0209 -0.4219 +20.98  
 C 3: -0.0042 -0.4038 8.51  
 C 2: -0.1030 -0.4519 3.20  
 C 4: -0.1062 -0.5349 1.23  
 C 5: -0.0739 -0.5346 1.52  
 C 6: -0.1541 -0.2790 0.84

Vertex: 2 tracks

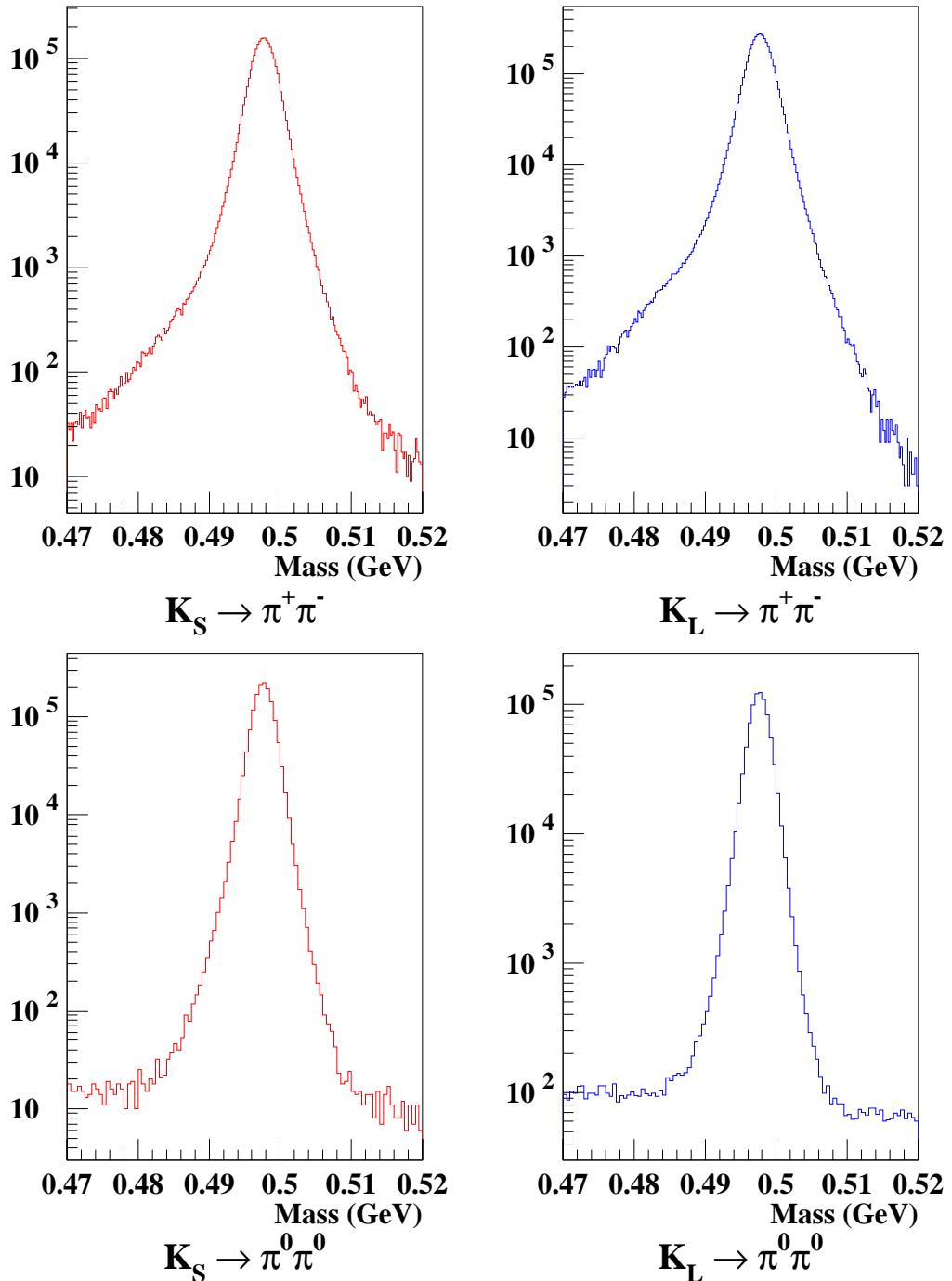
X	Y	Z
0.0944	-0.0032	138.075

Mass=0.4972 (assuming pions)  
Chisq=8.66 Pt2v=0.000042



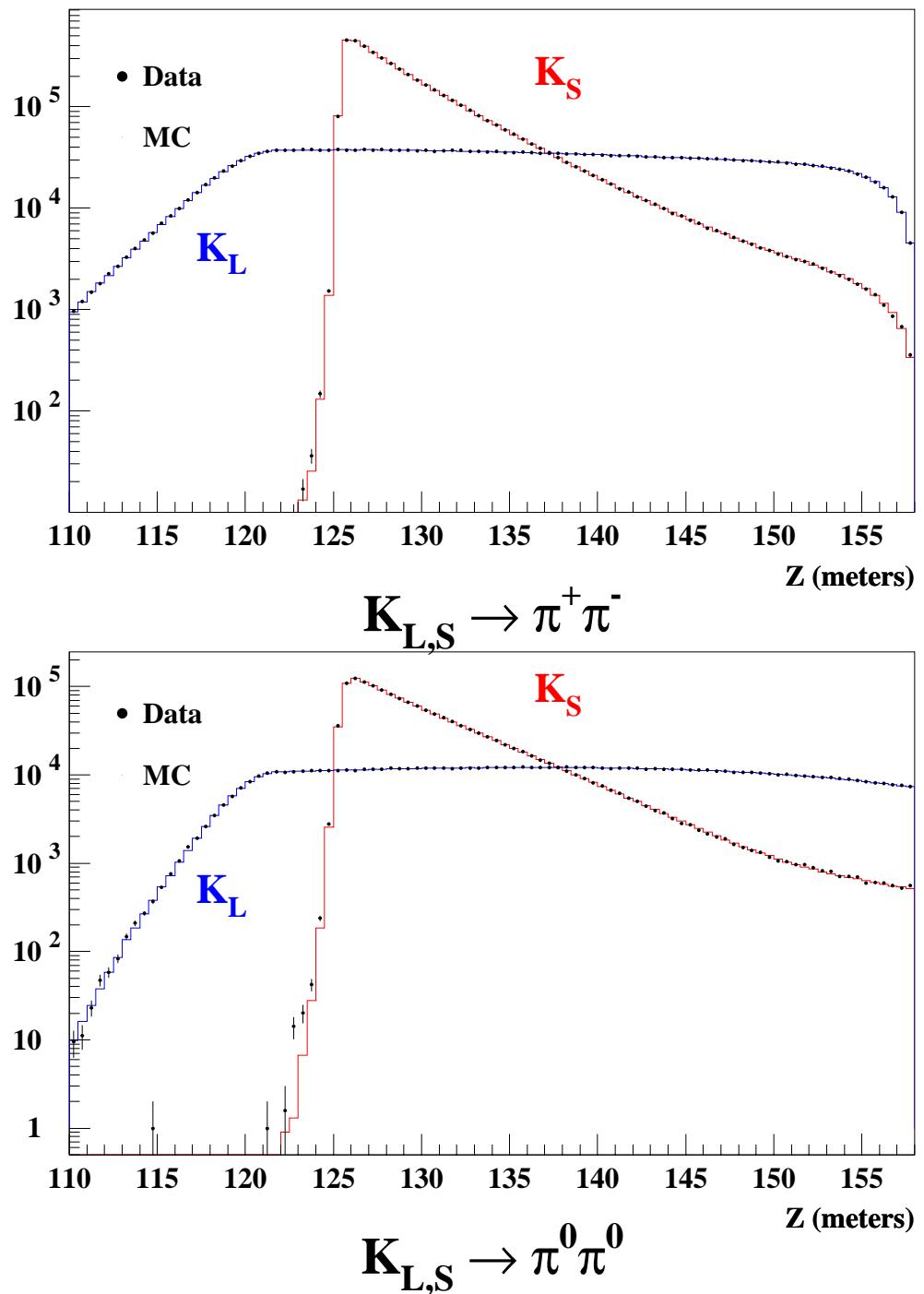
- - Cluster
- - Track
- - 10.00 GeV
- - 1.00 GeV
- - 0.10 GeV
- - 0.01 GeV

## Kaon Mass Peaks



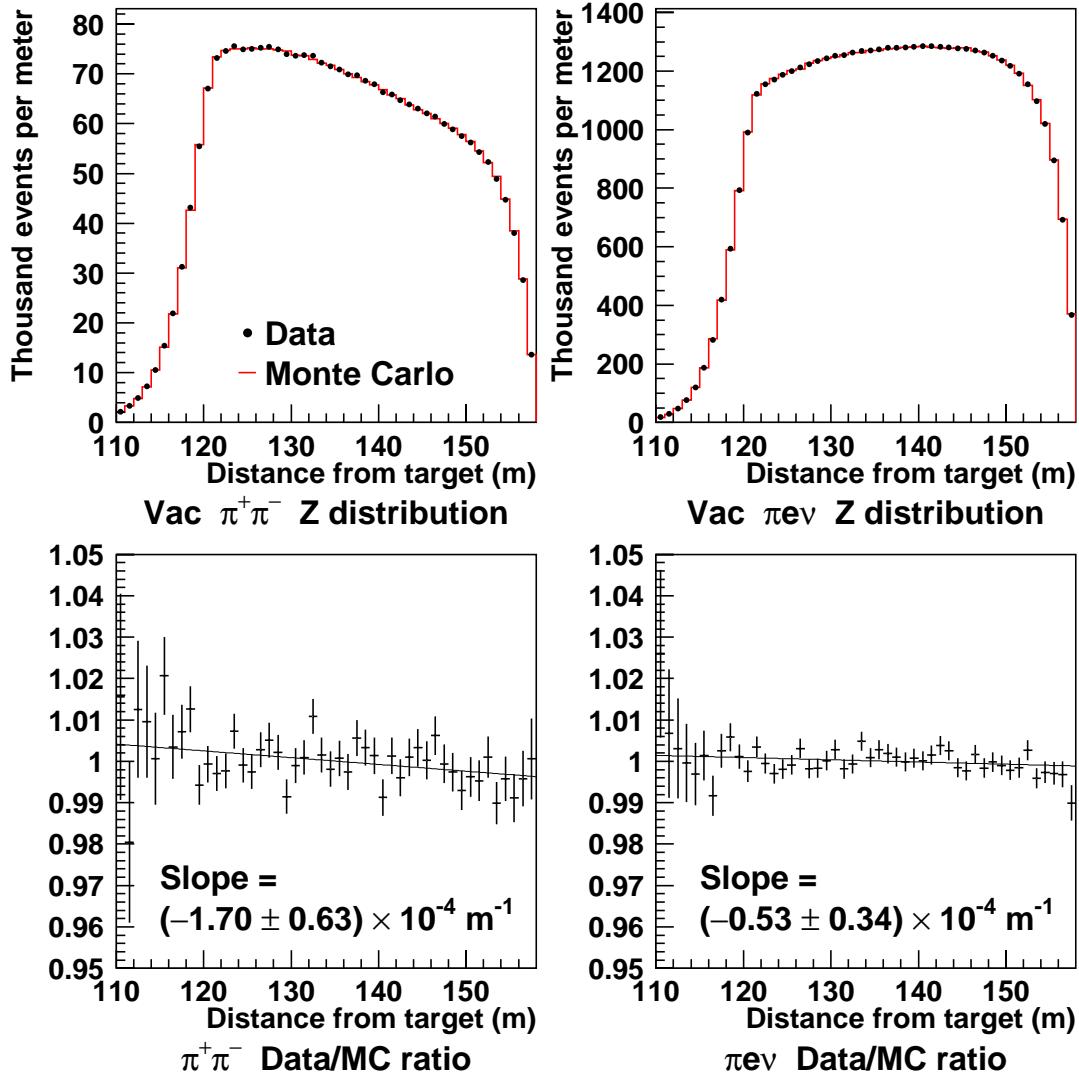
Kaon mass peaks prior to background subtraction

## Kaon Decay Distributions



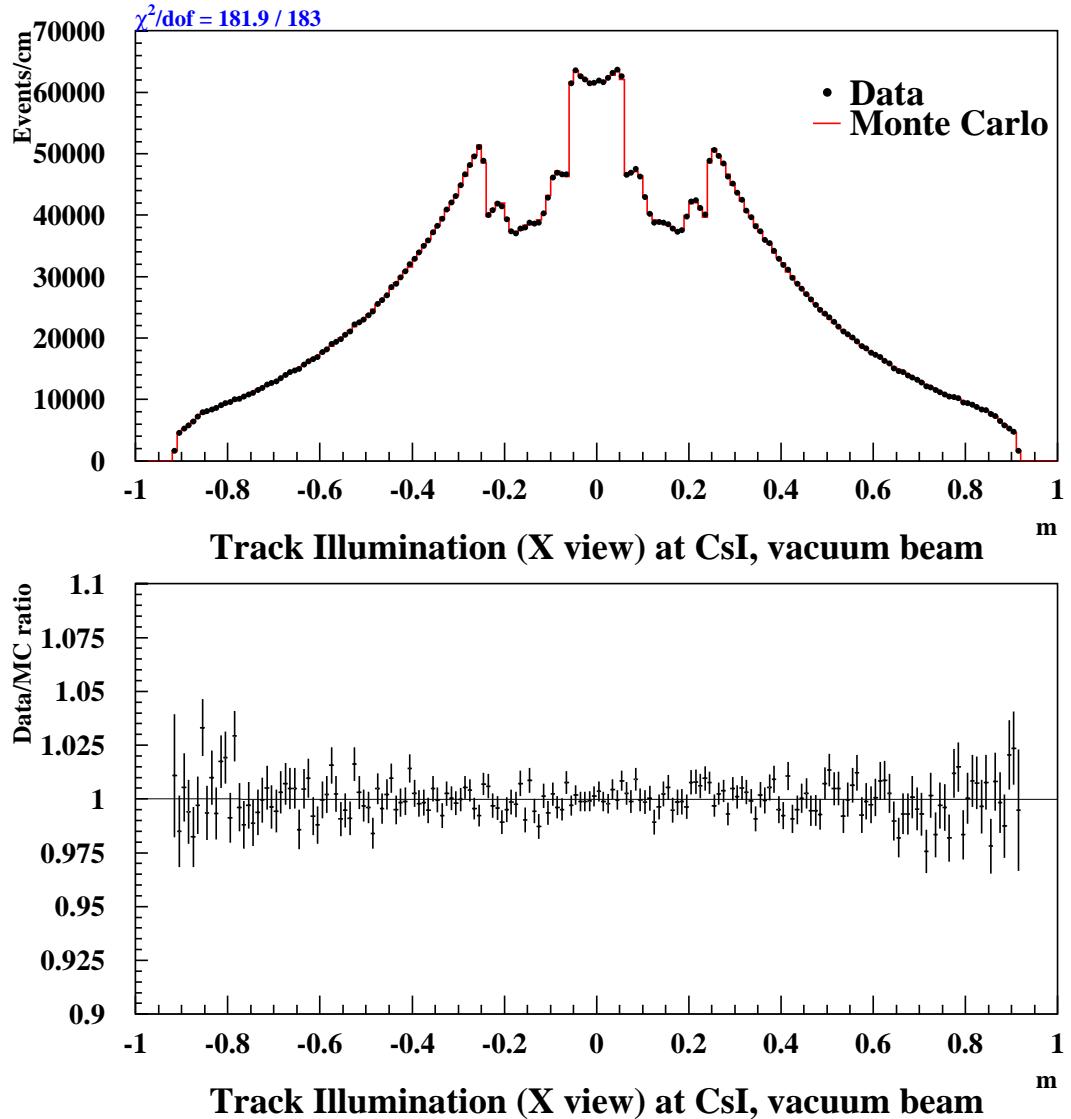
## $K \rightarrow \pi^+\pi^-$ Decays - Acceptance Corrections

Verify  $K \rightarrow \pi^+\pi^-$  acceptance using  $K_L \rightarrow \pi^\pm e^\mp \nu$  decays.



There is a slope in the ratio of Data/Monte Carlo for  $K_L \rightarrow \pi^+\pi^-$ . KTeV assigns a systematic uncertainty of  $1.6 \times 10^{-4}$  on  $\epsilon'/\epsilon$  to account for this discrepancy.

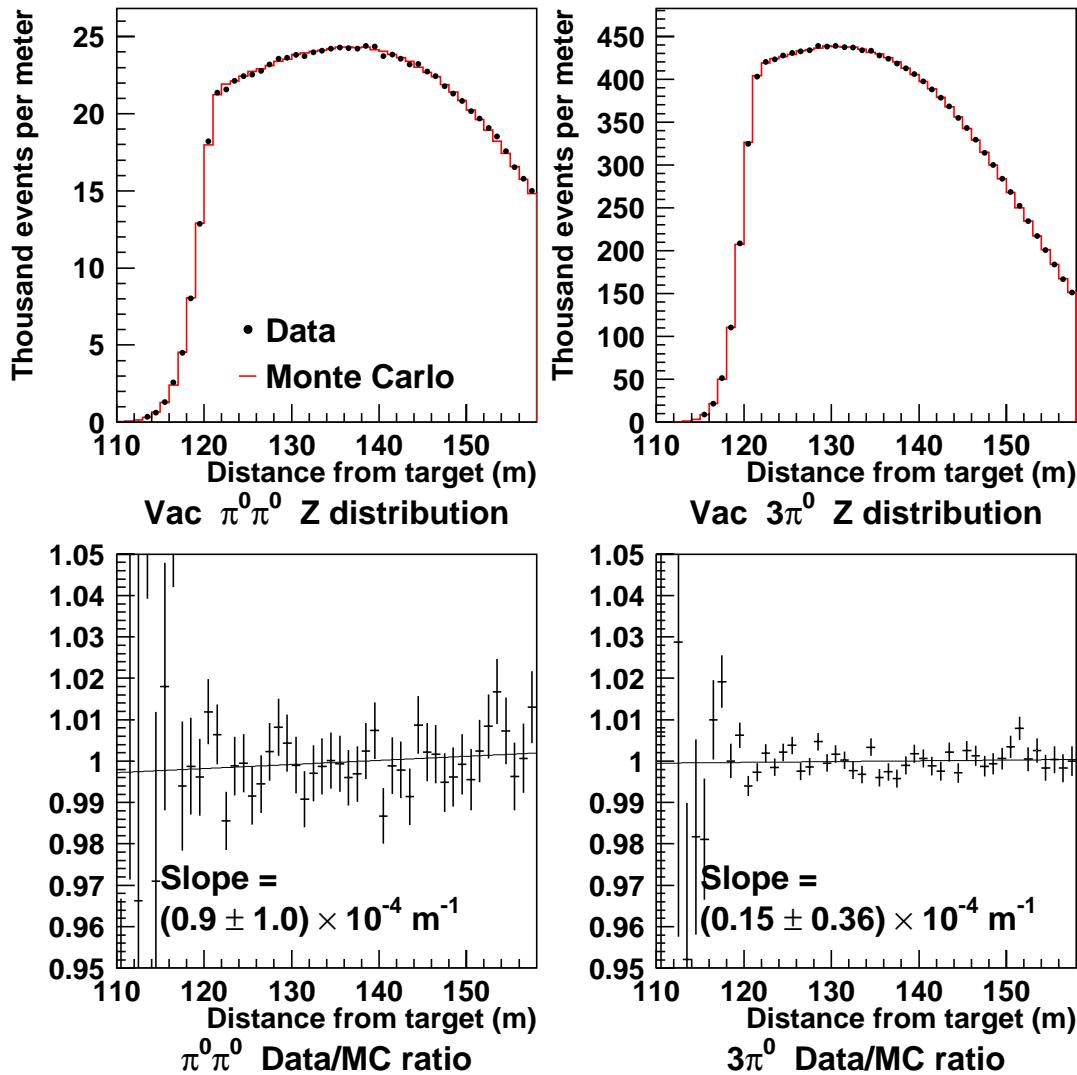
## Detector Occupancy for Charged Mode



The Simulation accurately models the Track Illumination for the  $K \rightarrow \pi^+ \pi^-$  decay modes.

## $K \rightarrow \pi^0\pi^0$ Decays - Acceptance Corrections

Verify  $K \rightarrow \pi^0\pi^0$  acceptance using  $K_L \rightarrow \pi^0\pi^0\pi^0$  decays.

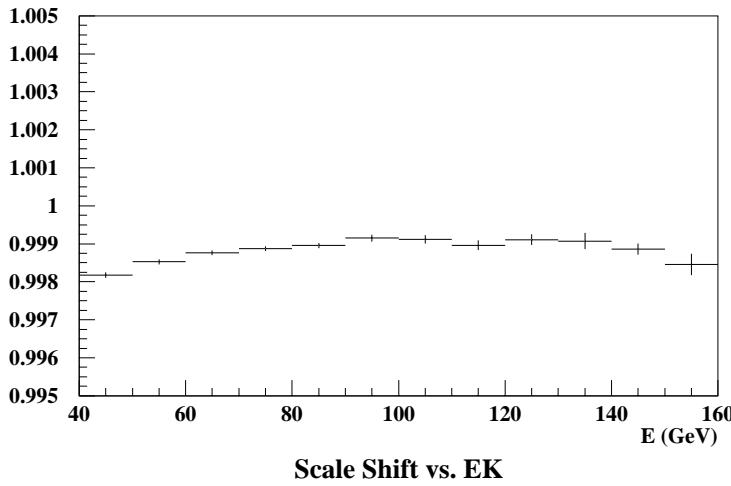
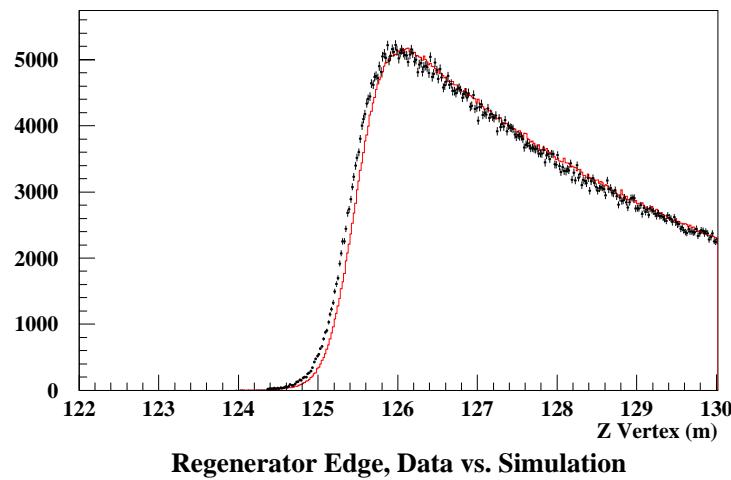


There is no significant slope in the ratio of Data/Monte Carlo for  $K_L \rightarrow \pi^0\pi^0$ . KTeV conservatively assigns a systematic uncertainty of  $0.7 \times 10^{-4}$  on  $\epsilon'/\epsilon$  based on the  $K_L \rightarrow \pi^0\pi^0\pi^0$  slope and error.

## Energy Scale Systematic - $K \rightarrow \pi^0\pi^0$ decays

Length of Decay region, and hence  $K_L$  Acceptance, is determined in  $K \rightarrow \pi^0\pi^0$  decays using the reconstructed Z vertex. However a shift in the calorimeter Energy scale will also shift the Z scale.

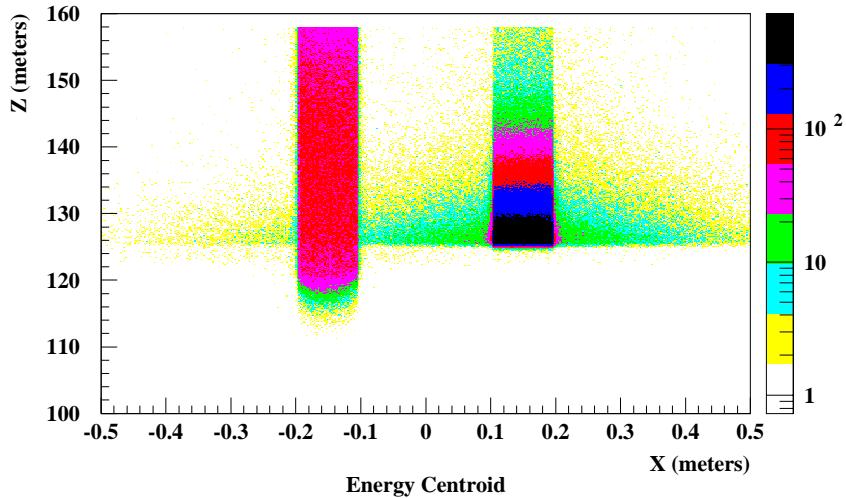
### Energy Scale in $K_S \rightarrow \pi^0\pi^0$ Events



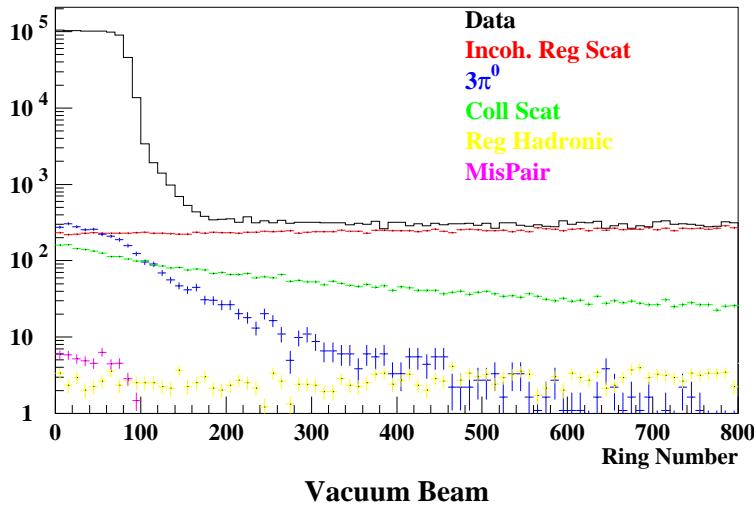
the Energy scale in KTeV was adjusted by 0.125% with a systematic uncertainty of 0.073%

## $K \rightarrow \pi^0\pi^0$ Backgrounds

For  $K \rightarrow \pi^0\pi^0$  decays  $K_L$  and  $K_S$  are separated using the Energy Centroid



Background is due to diffractive and inelastic regeneration, and is subtracted using a regeneration model fit to  $K \rightarrow \pi^+\pi^-$  data

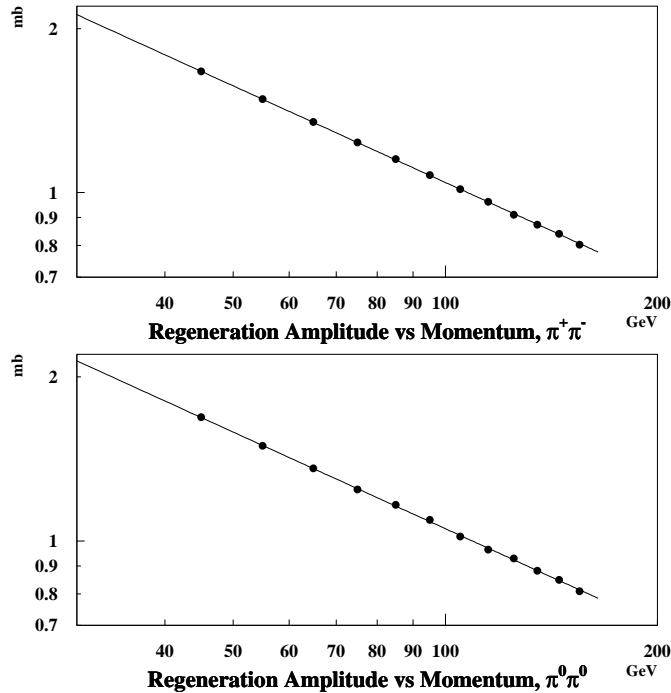


where the Ring Number is proportional to the distance from the center of the beam.

KTeV assigns a systematic error on  $\epsilon'/\epsilon$  of  $0.8 \times 10^{-4}$  from  $K \rightarrow \pi^0\pi^0$  backgrounds.

## $\epsilon'/\epsilon$ Fit and Blind Analysis

KTeV extracts  $\epsilon'/\epsilon$  from a fit to  
 $N_{K_L \rightarrow \pi^0 \pi^0}(E_i)$ ,  $N_{K_S \rightarrow \pi^0 \pi^0}(E_i)$ ,  $N_{K_L \rightarrow \pi^+ \pi^-}(E_i)$ ,  $N_{K_S \rightarrow \pi^+ \pi^-}(E_i)$   
the regeneration phase and amplitude are also fit



In addition KTeV performed the analysis **BLIND** to the value of  $\epsilon'/\epsilon$ . This was done by hiding the fitted value of  $\epsilon'/\epsilon$ , and instead looking at the parameter:

$$\{\epsilon'/\epsilon\}^* = \begin{Bmatrix} 1 \\ -1 \end{Bmatrix} \times \epsilon'/\epsilon + C$$

where  $C$  was an hidden constant with a sigma of 0.006, and the choice of  $-1$  or  $1$  was also hidden. The value of  $\epsilon'/\epsilon$  was hidden until one week before the result was announced.

## KTeV Result and Systematics

Systematics	$\pi^+\pi^-$ Analysis ( $\times 10^{-4}$ )	$\pi^0\pi^0$ Analysis ( $\times 10^{-4}$ )
Trigger (L1/L2/L3)	0.5	0.3
Energy Scale	0.1	0.7
CsI non-linearity	—	0.6
Calibration/Alignment	0.3	0.4
Analysis Cuts	0.6	0.8
Backgrounds	0.2	0.8
Apertures (incl Reg Edge)	0.3	0.5
Detector Resolution	0.4	< 0.1
DC simulation	0.6	—
Overall Acceptance	1.6	0.7
Monte-Carlo Statistics	0.5	0.9
Attenuation Slope	0.2	
Movable Absorber	0.2	
External Parameters	0.2	
Total Systematic	2.8	

KTeV Number of Events

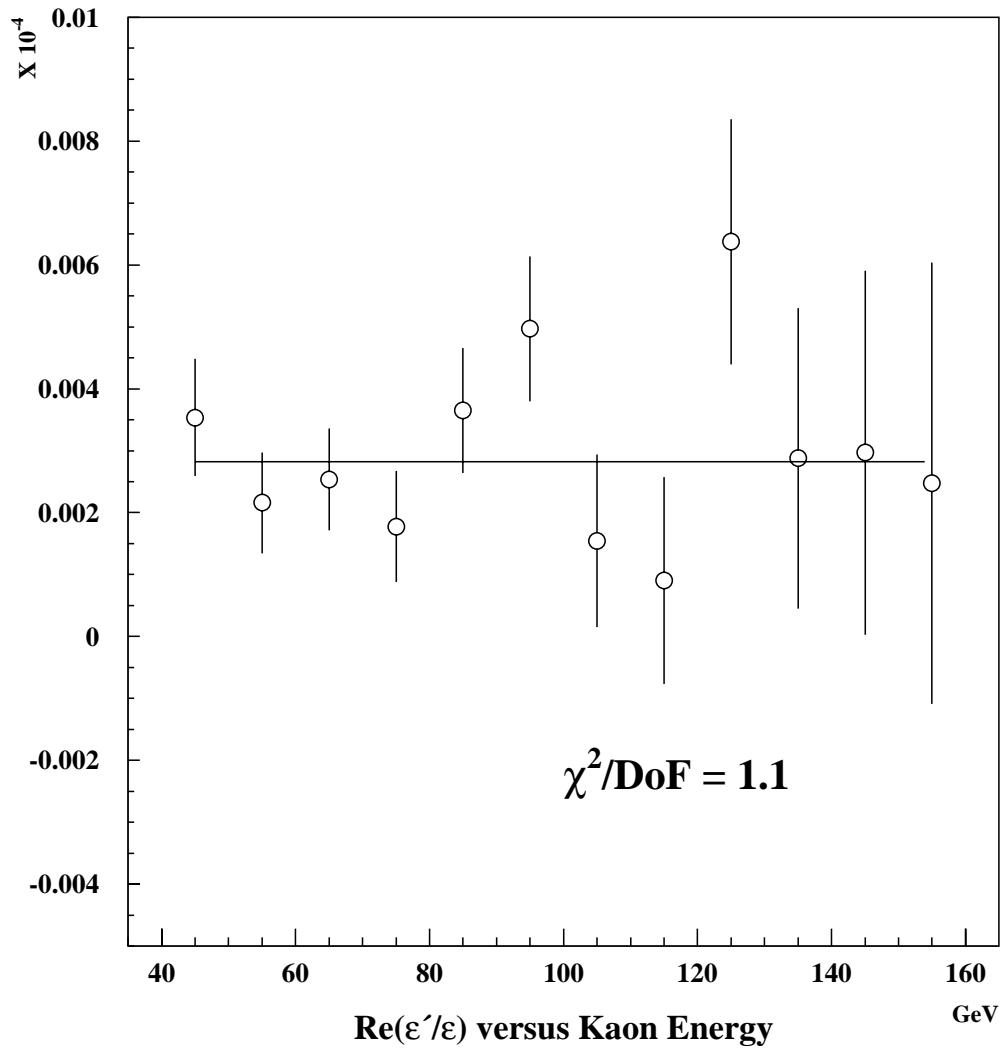
Decay Mode	events ( $10^6$ )
$K_L \rightarrow \pi^0\pi^0$	0.86
$K_S \rightarrow \pi^0\pi^0$	1.43
$K_L \rightarrow \pi^+\pi^-$	2.61
$K_S \rightarrow \pi^+\pi^-$	4.52

KTeV Result is

$$Re(\epsilon'/\epsilon) = (28.0 \pm 3.0(\text{stat}) \pm 2.8(\text{syst})) \times 10^{-4}$$

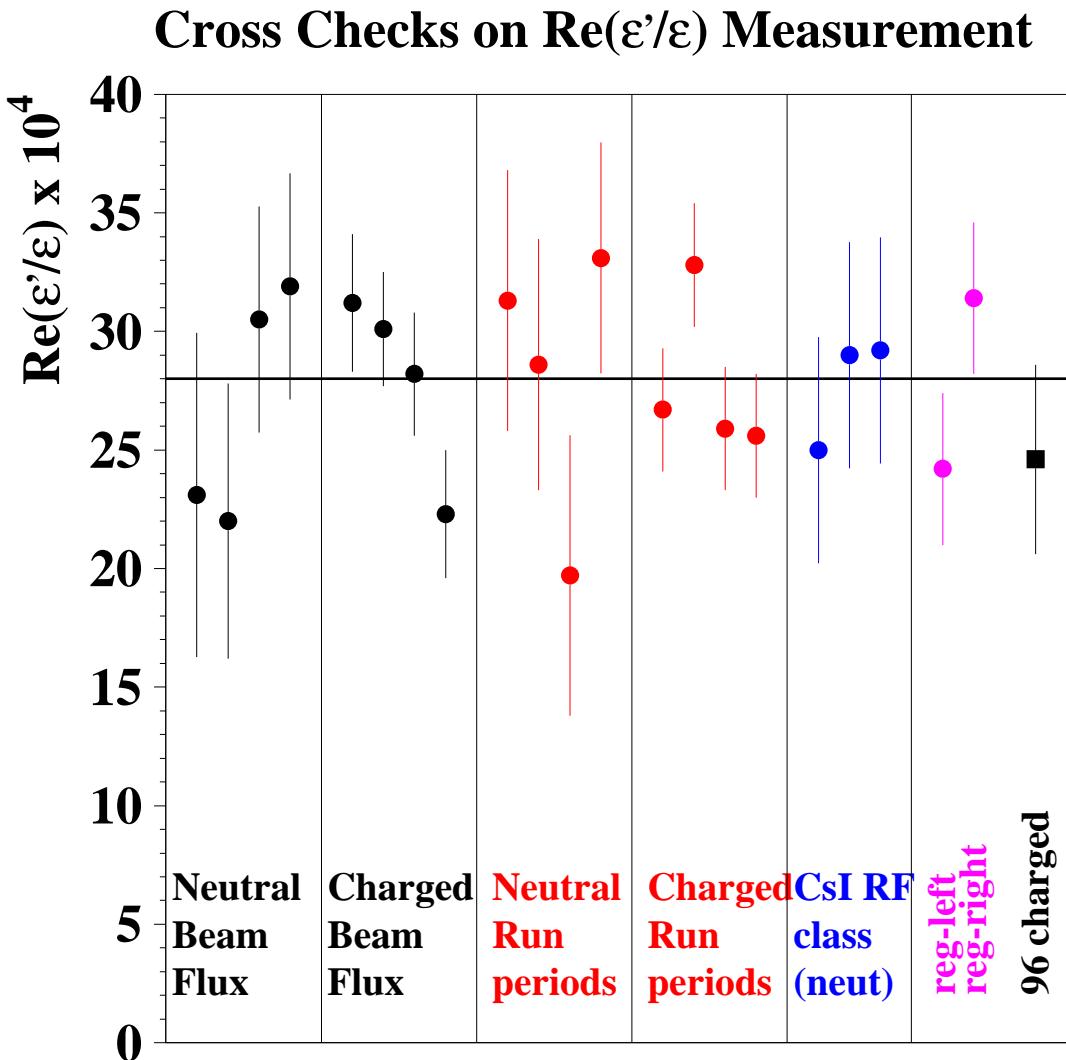
$$Re(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$$

## KTeV $\epsilon'/\epsilon$ vs. Kaon Energy



The  $\epsilon'/\epsilon$  fit is independent of Kaon Energy. The errors in this plot are purely statistical.

## KTeV Checks



Dividing data into various sub-samples shows no systematic effects.

Note that the KTeV result used  $K \rightarrow \pi^0\pi^0$  taken in 1996, and  $K \rightarrow \pi^+\pi^-$  taken in 1997; the  $K \rightarrow \pi^+\pi^-$  data from 1996 was not used because of a triggering problem which had a 20% inefficiency and an additional systematic uncertainty of  $4 \times 10^{-4}$ . As a check the 1996  $K \rightarrow \pi^+\pi^-$  data was analyzed and found to be consistent with the quoted result.

## CPT Tests

Interference in the Regenerator Beam  $K_L + \rho K_S$  is used to measure  $\Delta m$ ,  $\tau_S$ ,  $\phi_{+-}$ , and  $\Delta\phi$ .

Preliminary results assuming CPT

$$\tau_S = (0.8967 \pm 0.0007) \times 10^{-10} s$$

$$\Delta m = (0.5280 \pm 0.0013) \times 10^{-10} \hbar s^{-1}$$

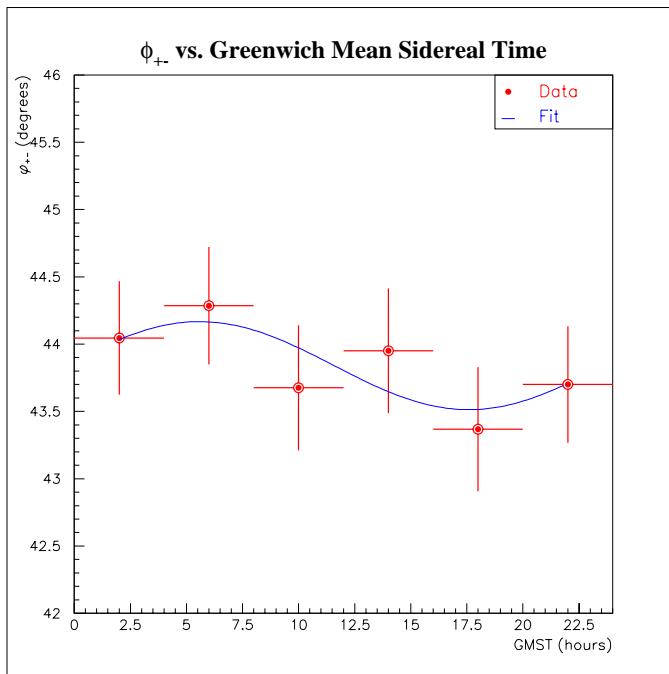
Preliminary results not assuming CPT

$$\phi_{+-} = 43.66^\circ \pm 0.30^\circ + 0.23^\circ \left( \frac{\Delta m - 0.5286}{0.0010} \right) - 0.26^\circ \left( \frac{\tau_S - 0.8967}{0.0010} \right)$$

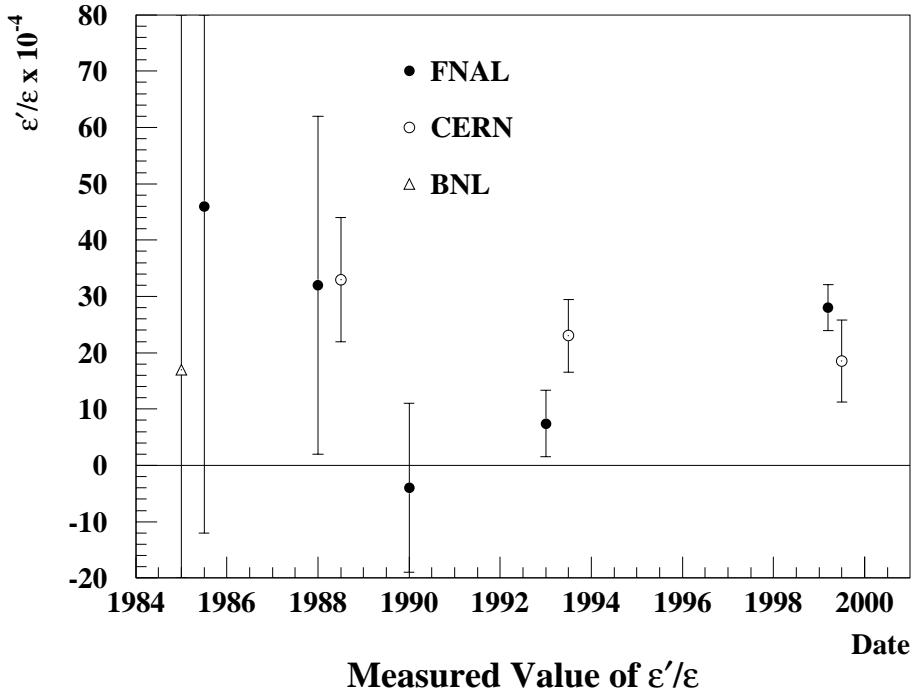
$$\Delta\phi = 0.09 \pm 0.43(\text{stat}) \pm 0.15(\text{syst})$$

and we can infer  $\frac{m_{K^0} - m_{\bar{K}^0}}{m_K} = (4.5 \pm 3) \times 10^{-19}$

Preliminary results show no time dependence in  $\phi_{+-}$



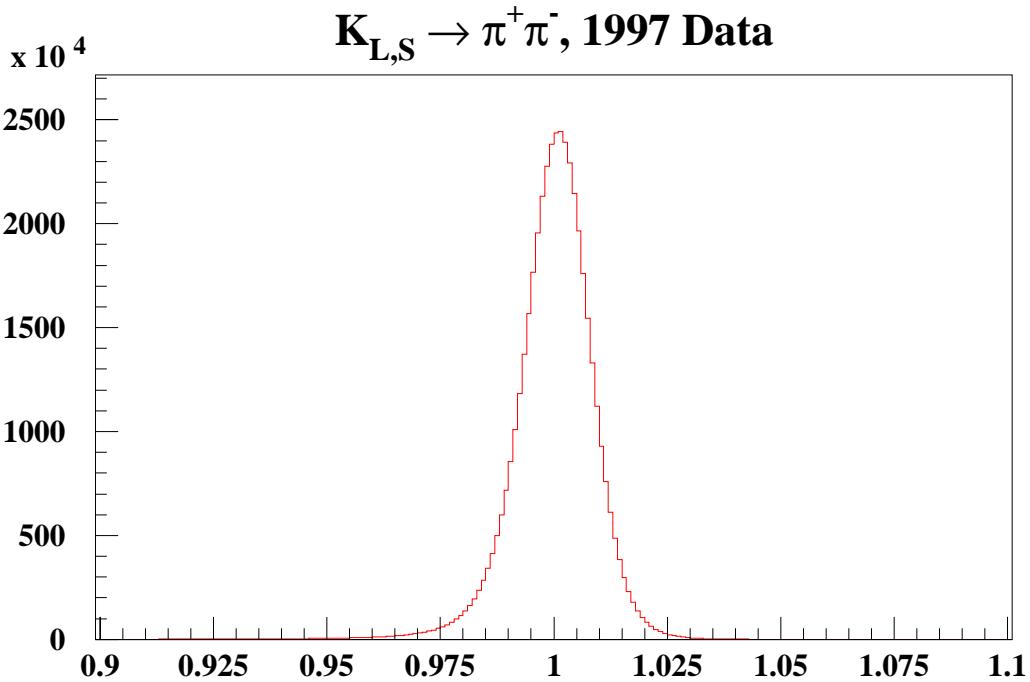
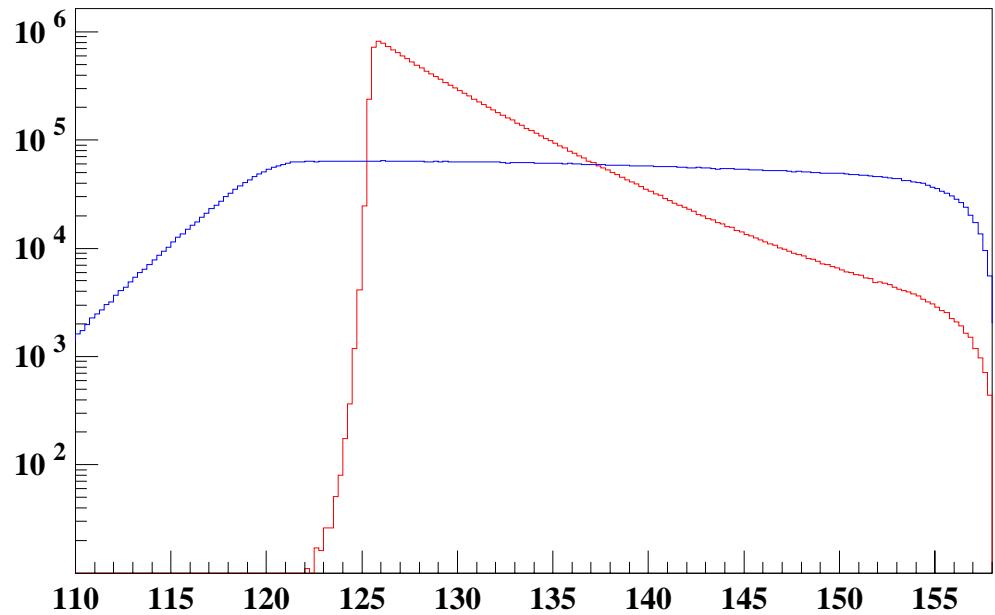
## $\epsilon'/\epsilon$ Measurements



Combining recent  $\epsilon'/\epsilon$  measurements

Experiment	$\epsilon'/\epsilon \times 10^{-4}$	
E-731	7.4 ± 6.0	
NA-31	23.0 ± 6.5	
KTeV	28.0 ± 4.1	
NA-48	18.5 ± 7.3	
Average	21.2 ± 2.8	$\chi^2/dof = 2.8$
Average	21.2 ± 4.7	scaled error

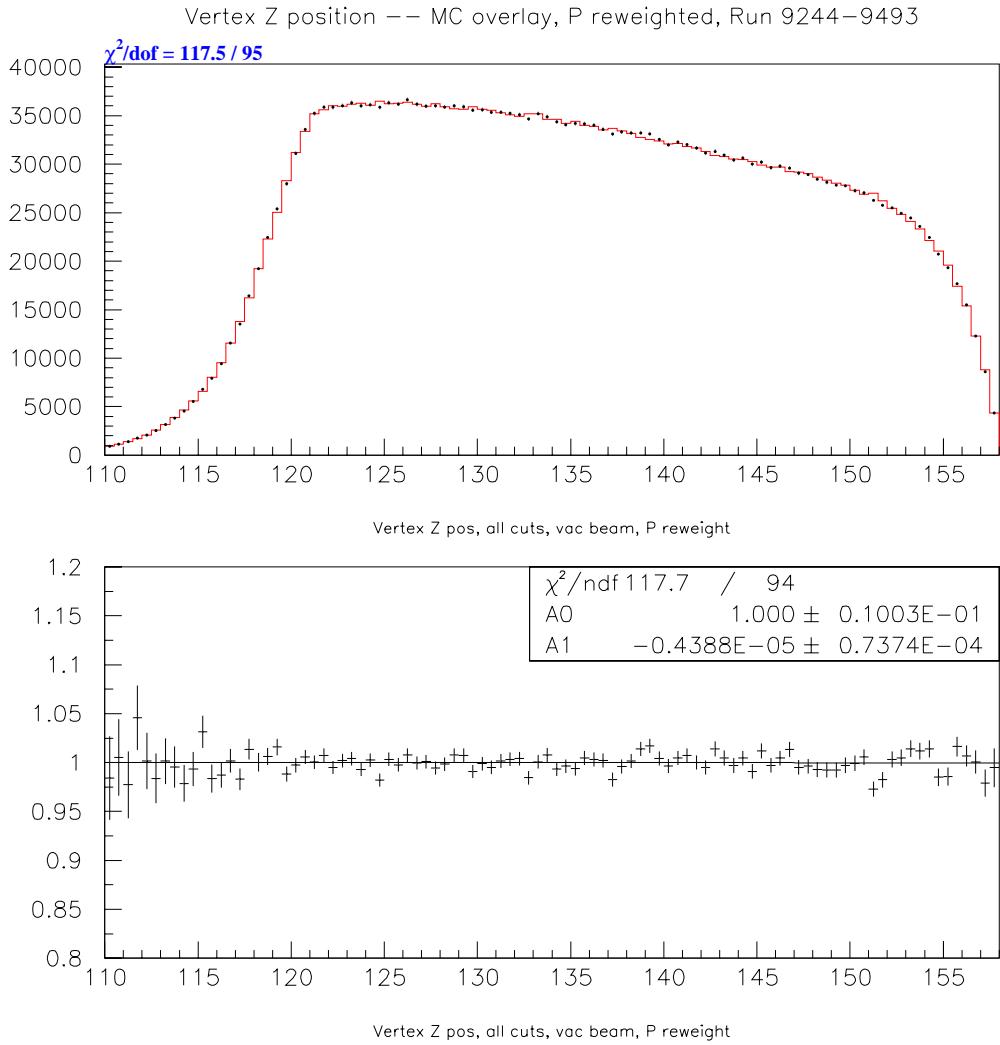
## KTeV 1997 Data



E/P Electrons, 1997 Data

The Analysis of the full 1997 data sample is on-going.

# KTeV 1997 $K_L \rightarrow \pi^+ \pi^-$ Acceptance



Preliminary comparisons of the decay distribution for the 97b Data set shows no significant slope between data and simulation.

## Prospects

- KTeV 1996-1997  $\epsilon'/\epsilon$  run

The entire KTeV 1996-1997 run has four times more data than the published sample - for a total of more than  $5 \times 10^6$   $K_L \rightarrow \pi^0\pi^0$  decays. Analysis is ongoing, with a goal of making a preliminary evaluation of the systematic error, with detailed Data vs. Monte-Carlo comparisons, by next spring. The analysis of the full 1996-1997 run is also being done blind to the  $\epsilon'/\epsilon$  result.

- KTeV 1999  $\epsilon'/\epsilon$  run

KTeV completed a very successful  $\epsilon'/\epsilon$  run this fall. The data collected is roughly equivalent to the 1996-1997 sample, thus the ultimate KTeV data sample should correspond to a factor of 8 more data than the published sample. This implies an ultimate statistical uncertainty of  $\pm 1 \times 10^{-4}$ .

Improvements for the 1999 run include reduced inefficiencies in the Drift Chamber and much more reliable CsI Calorimeter electronics.

- $\epsilon'/\epsilon$  Predictions

Optimism that predictions can improve  
Re-examination of theoretical uncertainties  
Lattice QCD